Imaging Performance Study: External Occulters

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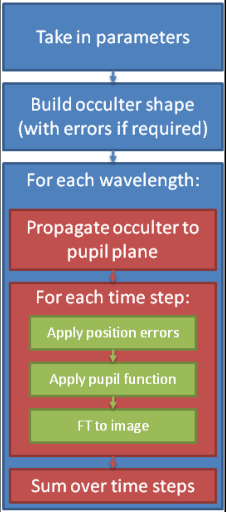
Occulter modeling requirements

Model propagation from occulter to image plane at a range of wavelengths

Incorporate realistic errors on occulter (position, orientation, shape), with the possibility of time-variance.

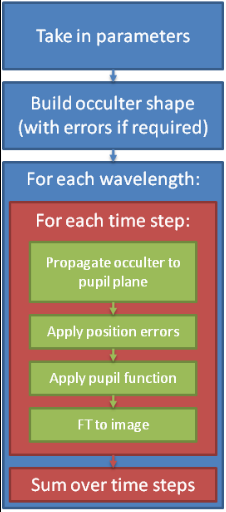
Capture occulter control realistically (spin rate, formation flying)

Instrument modeling block diagrams

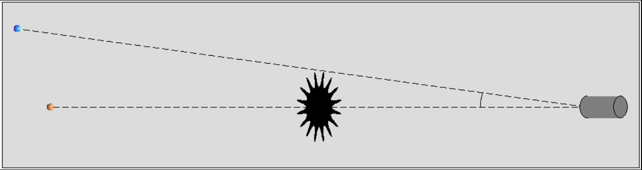


Flow in instrument modeling depends on input parameters.

Depending on what types of images are requested and how many of each, different approaches may be more efficient.



Errors on occulters



Errors come in three varieties:

1. Position: relative misalignment between occulter and telescope. Relaxed in the longitudinal direction by a factor of 10^6! ($\sim$ 1m lateral vs. 1000km longitudinal)
2. Orientation: tilt of the occulter away from perpendicular to the telescope-star axis. Well-modeled by taking the projection of the occulter onto plane perpendicular to the axis. (Roll comes under this as well, but doesn't affect suppression levels.)
3. Shape: Changes in the occulter shape from manufacturing, deployment, thermal, and vibrational sources. The first two are modeled as static, and the second two as transient effects.

Propagation algorithms

Fourier transforms require unfeasibly large matrices to accurately capture the structure of an occulter edge: full shade is tens of meters and edges need to be specified to tens of microns, which means $\sim 10^6 \times 10^6$ grids.

Instead, currently using two algorithms:

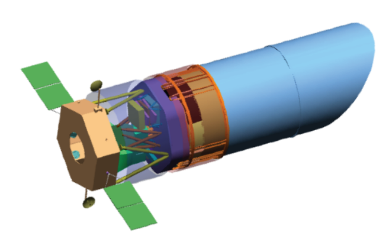
1. Bessel function expansion (Vanderbei, Cady, and Kasdin 2007).
   - Pros: Extremely fast near optical axis, can do all position errors, can be used to get any point in the pupil plane.
   - Cons: Cannot do orientation or shape errors without modification, computation time increases linearly with distance from optical axis.
2. Dubra-Ferrari integral (Dubra and Ferrari 1999).
   - Pros: Can do all position/orientation/shape errors, roughly same computation time at every point.
   - Cons: much slower for simpler cases, calculating points outside geometric shadow of occulter is very difficult.

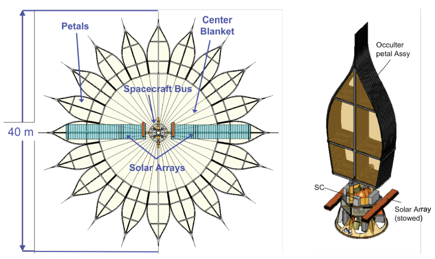
Algorithm switched depending on input parameters.

Point design for testing: THEIA

THEIA (Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy) (Kasdin *et al.* 2009)

- Developed as part of the Astrophysics Strategic Mission Concept Studies
- 4m on-axis UVOIR telescope designed to work jointly with an occulter





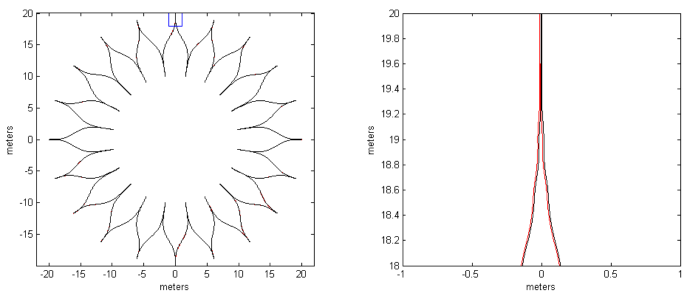
Top. ITT *Bottom.* Lockheed Martin

THEIA optical properties and key parameters

- Edge shaped to provide suppression of diffraction effects over 250 – 700nm (i.e. $\Delta\lambda/\lambda \approx 95\%$ in UV/visible)
- 20 petals, each 10m long. Gaps between petals $\geq$ 1mm, tip width $\geq$ 1mm; shape chosen by optimization.
- Starlight is removed to $\geq 10^{-10}$ prior to reaching the telescope; does not require wavefront control
- Large and far from telescope: 40m in diameter, 55000km distant (can move in to 35000km to extend suppression to 1100nm)
- Inner working angle set by geometry at 75mas, independent of wavelength and telescope size (up to limits of occulter shadow). 50% throughput point at 60mas
- On-axis telescope; assumes 30% circular secondary and ignores spiders

Shape errors

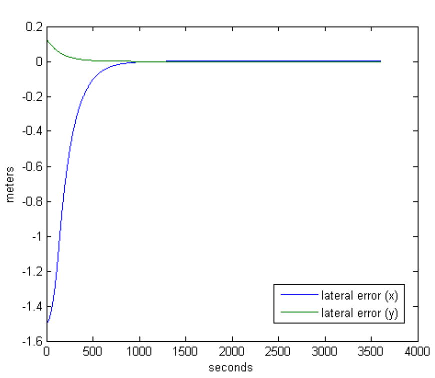
Perturbation	Requirement	Units
Proportional width	7×10^{-5}	-
Tip clip (distance from end)	10	mm
In-plane bend (quadratic)	20	mm
Symmetric petal edge error (rms)	70	μm
Antisymmetric petal edge error (rms)	70	μm

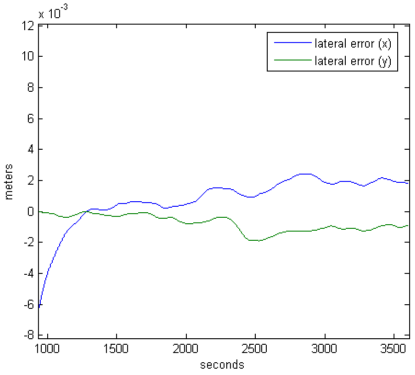


Edge error modeled as falling off as k^{-3}. Code can apply others, but these are the main performance drivers.

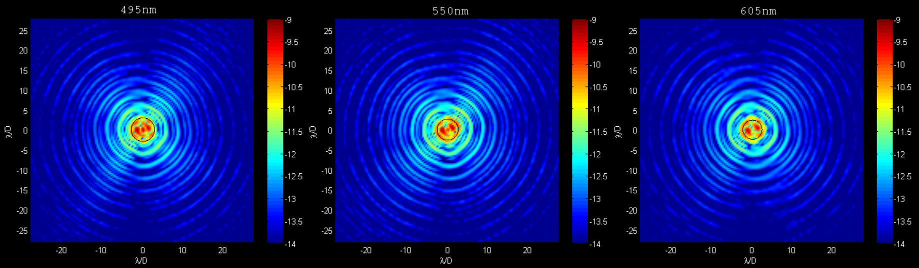
Lateral tolerance

Occulter position sensing done out-of-band; significantly higher flux in shadow and can be done with a low-resolution sensor (See e.g. Sirbu and Kasdin 2011)



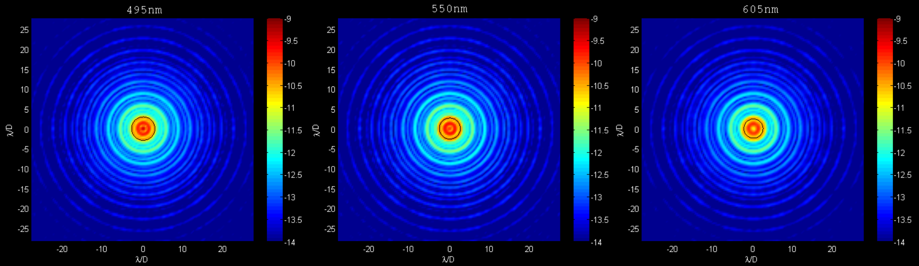


Sample data product (instantaneous)



A single snapshot of the image plane field, using all static errors shown previously and a (single) lateral offset. IWA shown by black circle.

Sample data product (integrated)



Uses all errors and tolerances shown previously, as well as rotating at 1 revolution per hour. Represents one hour exposure, with images made at 1s intervals and summed to incorporate lateral motion and spin. Shape errors are treated as static. IWA shown by black circle.

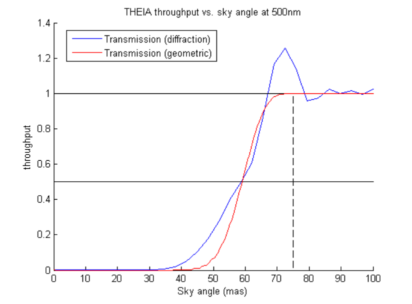
Known simplifications and idealizations

- No finite stellar size
  - For most stars, finite stellar size will tend to decrease lateral tolerance of occulter by a few cm
- No wavefront errors in telescope
  - Diffraction-limited telescope; star light scattered from residual aberrations in the optics will have intensity $\ll$ than the planet peak
- No dynamic errors
  - Should be similar performance to static case as long as errors stay within requirements
- No telescope pointing errors or rolls
  - Will tend to smear starlight; will not affect suppression level.
- Imperfect off-axis transmission function (see next)

Transmission function (for everything except star)

Geometric optics predicts off-axis transmission to follow the occulter shape.

Diffraction calculations show significant deviations from this, including enhancement at the inner working angle above unity (a feature that cannot be captured by geometric optics). Also has wavelength dependence. However, will enhance exozodi as well.



Currently using geometric optics for speed. Does not affect residual starlight.

Future improvements to fidelity

Optional augmentation to existing simplifications:

- Inclusion of stellar angular size
- Dynamic errors, particularly models of thermal behavior with spin
- Better modeling of manufacturing errors (following upcoming TDEM results)
- Specification of transmission functions

and new functionality:

- Micrometeorite damage: model as pinholes that appear at specific times in an integration
- Expanded propagation algorithms:
    - Modified bessel function expansion (Cady 2010): extends the Bessel expansion to arbitrary orientation/shape errors, but can be quite slow.
    - Boundary diffraction wave approach: similar to Dubra-Ferrari, but without the limitation on the geometric shadow.
- Incoherent effects (edge glint, back-illumination)

Additional slides

THEIA properties and operational constraints

- No outer working angle; 360° discovery zone
- Slews continuously to fly in formation with the telescope and target star; requires ~ 2 week retargeting maneuvers between observations
- $25 - 30\%$ of telescope time usable with occulter; rest for general astrophysics
- Two other instruments along with exoplanet camera: UV spectrograph and wide-field camera
- Targets limited by sun angle ($45^\circ - 85^\circ$)